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ON-LINE INSPECTION AND THERMAL PROPERTIES COMPARISON
FOR LASER DEPOSITION PROCESS

by

YU YANG

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MANUFACTURING ENGINEERING

2007

Approved by

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PUBLICATION THESIS OPTION

This thesis consists of the following two articles that have been submitted for publication as follows:

Pages 2-31 has been submitted to the EIGHTEENTH SOLID FREEFORM FABRICATION SYMPOSIUM 2007.

Pages 32-40 has been accepted and published in the SEVENTEENTH SOLID FREEFORM FABRICATION SYMPOSIUM 2006.

ABSTRACT

Laser deposition is a rapid prototype technology that can directly build solid metal parts from metallic powder by depositing metal cladding to fabricate and repair components. The two parts of this thesis are focused on comparing the laser deposition cladding with intended design model and comparing the effect of laser deposition process on thermal properties with traditional welding process.

The first part of the thesis uses a non-contact 3-D scanner equipment to inspect the free-form and complex parts built by laser deposition. Registration of the measured data and 3-D Computer Aided Design (CAD) model and comparison between the two are conducted to determine if the deposition is sufficient for fabricating a part.

The second part investigates comparison of thermal properties of laser deposition and traditional welding process via thermal diffusivity measurement. The experiment system based on the laser flash method was designed and conducted. The results show that traditional welding repaired H13 tool steel parts have lower thermal diffusivity and conductivity than virgin metal and the parts repaired by laser deposition have higher thermal diffusivity and conductivity. It means that laser deposition process will be better for part repair considering the thermal diffusivity and thermal conductivity than traditional welding process.

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INTRODUCTION

This thesis is focused on comparing the laser deposition cladding with intended design model and comparing the effect of laser deposition process on thermal properties with traditional welding process. It is research on two aspects of laser deposition cladding. The first part of the thesis is aimed at solving the geometric inspection of laser deposition cladding, and the second part is for comparing the thermal properties of laser deposition cladding to samples of conventional welding process.

PAPER I

LASER DEPOSITION CLADDING ON-LINE INSPECTION USING 3-D SCANNER

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ABSTRACT

Laser deposition directly deposits metal cladding to fabricate and repair components. In order to finish the fabrication or repair, 3-D shape of the deposition needs to be inspected, and thus it can be determined if it has sufficient cladding to fabricate a part after deposition process. In the present hybrid system in the Laser Aided Manufacturing Lab (LAMP) at the University of Missouri - Rolla, a CMM system is used to do the inspection. A CMM requires point-by-point contact, which is time consuming and difficult to plan for an irregular deposition geometry. Also, the CMM is a separate device, which requires removal of the part from the hybrid system, which can induce fixture errors. The 3-D scanner is a non-contact tool to measure the 3-D shape of laser deposition cladding which is fast and accurate. In this paper, A prototype non-contact 3-D scanner approach has been implemented to inspect the free-form and complex parts built by laser deposition. Registration of the measured model and 3-D CAD model allows the comparison between the two models. It enables us to determine if the deposition is sufficient before machining.

Keywords

Laser deposition, 3-D scanning, free form, part comparison, inspection

I. INTRODUCTION

Rapid prototype technologies are gaining more and more interests in industries for the reasons that they can fabricate the components directly from 3-D computer-aided-design (CAD) model and save time and cost as well. Laser deposition is a rapid prototype technology that can directly build solid metal parts from metallic powder, such as Tool steel, Titanium, etc. One of the advantages of laser deposition is that it can deposit free-form surfaces and complex geometries. In the Laser Aided Manufacturing Processes (LAMP) lab at the University of Missouri - Rolla, a hybrid system was developed to deposit metallic powder to build or repair a part. After deposition, the hybrid system machines it to fabricate the part.

Examination of the deposition cladding indicates that the interdependence of laser power, powder feed rate into the melt pool, relative traverse speed of the part and retained heat effects cause difficulty in precisely controlling the deposition cladding profile [1]. So it is important to inspect the deposition cladding. To verify the acceptance of a deposited component before it is machined by CNC, one needs to compare the measured data with the intended CAD design model to determine if it is sufficient to be manufactured into a component afterwards.

In the present hybrid system, a Coordinate Measuring Machine (CMM) system is used to do inspection. Despite its great accuracy, CMMs have some drawbacks, for example, CMMs need point by point contact inspection, they are slow and the probe size

limits the smallest area that can be inspected, which makes it difficult to inspect the complex geometry or free form surface [2]. In this paper, a 3-D scanner is used to inspect the surface of the laser cladding. It is fast and has sufficient accuracy for on-line inspection.

The main idea behind the research in this paper is to align the measured surface with the 3-D CAD model and then compare the two top surfaces. Before comparing measurement data to the 3-D CAD model, it is necessary to align the model with the scan data. This process is called registration, which is to transform the Scanner Coordinate System (SCS) and the Design Coordinate System (WCS) into one coordinate system. Then the algorithm creates parallel planes to slice both the 3-D CAD model and scanned model in the x and y directions. The intersections of 3-D CAD and scanned model are calculated. The comparison of the 3-D CAD model with the measurement model is transferred to compare these points and it will show the height difference and then determine if the measured component is sufficient or not at a (x, y) position. Any absent volume can be identified and re-deposited later.

II. EQUIPMENT OVERVIEW

In the Laser Aided Manufacturing Processes (LAMP) lab at the University of Missouri – Rolla, a Layered Manufacturing process was developed which use a laser to create a molten pool and then feeds the metal powder into the pool to create a deposition cladding layer by layer. The system in the LAMP lab consists of a 1.0 KW Nuvonyx diode laser (808 nm wavelength) (Fig. 1) with integrated 5-axis FADAL CNC (Fig. 2), Bay State thermal spray powder feeder, on line control system, etc.



Figure 1. 1.0 KW Nuvonyx Diode Laser (808 nm wavelength)



Figure 2. Integrated 5-axis FADAL CNC and Laser Deposition Head

A Nextengine 3-D scanner (Fig. 3) is used to inspect the deposition cladding. It takes about 2 minutes per scan of each facet with the dimensional accuracy of 0.005 inch in macro mode and 0.015 inch in wide mode [3]. In order to construct a complete surface model, several facets need to be scanned and registered together manually. It takes much more time to do several scans and the registration of images. In fact, the deposition cladding is always deposited on the top and one scan from the top can acquire the surface and substrate information for the subsequent registration and comparison for most parts.

III. RELATED WORK

3.1. Registration

Traditionally, localization¹ is achieved by presenting the part at a desired position and orientation, using special tools, fixtures or some device especially designed for the

¹ In this paper, the term of “registration” is used instead of “localization” in references.

part. It is usually costly, time and efforts are needed to design the special fixture for a new part. Recently, localization has been implemented by aligning the parts' SCS to the DCS by using some measured data [2].



Figure 3. A Nextengine 3-D scanner with 0.005 inch accuracy in macro mode and 0.015 inch accuracy in wide mode

The 3-2-1 approach, which measure datums to establish a reference frame for the part, is conventionally used in contact inspection. Three points are measured to establish the first plane, then two points are measured from second plane perpendicular to the first. At last, one point is measured from the last datum perpendicular to those two [2].

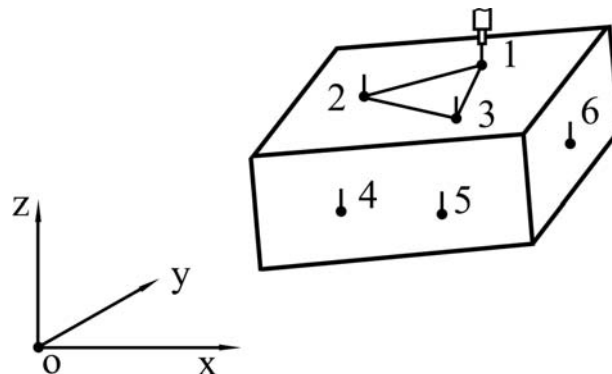


Figure 4. Traditional 3-2-1 approach for registration to establish three perpendicular reference frames

The prevalent approach in registration is the Iterative Closest Point (ICP) method. ICP tries to find the minimum distance between two surfaces [2]. It is effective to do point to model matching for complex and free-form surface inspection. However, in laser deposition, in order to get the profile information of deposition, not only the individual surface or profile information, but the relative location information to reference datum is required. For example, in Fig. 5, “a” shows the result of registration of two top surfaces by ICP without the reference plane. “b” shows the ideal registration for the laser deposition, which registered the substrate of the part to the corresponding bottom of design model. Obviously in “a”, ICP is not effective to determine if the cladding is eligible for fabricating a part only by the registering the top surface. In fact the reference plane and side walls need to be registered and inspected.

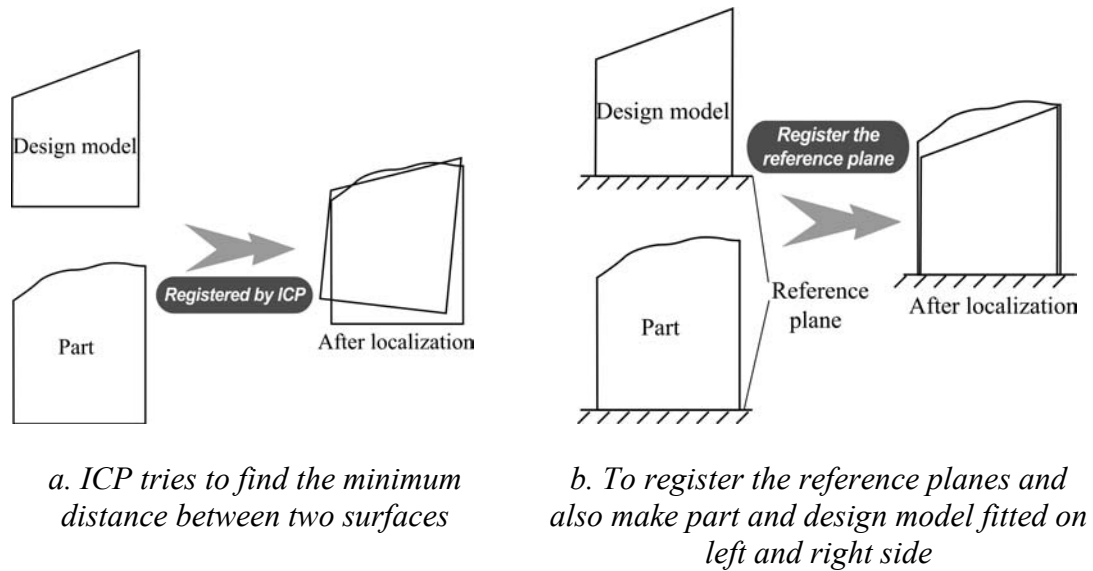


Figure 5. Registration by ICP vs. desired registration for laser deposition

3.2 Surface description methods for registration and comparison

Surface description is a basic task and all subsequent operations are based on it. Earlier works describes the parts by certain primitives such as point, line and plane, and/or polyhedral approximations. Later research works applied higher order forms of

surface representation. Many approach use parametric description of the surfaces, such as parametric splines, Coons, Bezier, B-spline and NURBS surface models. With the development of non-contact measurement methods, which normally obtain the dense data volume and always with arbitrary topology, results in manual interaction due to the topology issue and/or accuracy degrading in establishing the surface model. Some recent research used the surface description methods, such as triangular meshes, other than traditional approaches such as B-spline, NURBS or others.

IV. REGISTRATION OF MEASUREMENT COORDINATE SYSTEM AND DESIGN COORDINATE SYSTEM

4.1. Coordinate systems for laser deposition inspection

There are four coordinate systems involved in laser deposition process: Design Coordinate System (DCS), Machine Coordinate System (MCS), Workpiece Coordinate System (WCS), and Scanner Coordinate System (SCS). In Fig. 6, 3-D model is designed and used to create CNC codes for deposition in DCS. It is also used to do comparison after deposition. In Fig. 7, a part is deposited on substrate on CNC machine in MCS and scanned in SCS. MCS defines machining head and laser head to determine the traverse track. WCS is detached on Workpiece and is on the substrate. The zero points of x, y, and z axis of MCS is set on substrate. The surface of substrate is adjusted to be level and the axes of WCS are set to be parallel to those of MCS, so the deposition traverse track is parallel to the axes of WCS and the deposition layers are parallel to the substrate. In order to compare the design model in Fig. 6 with the Workpiece in Fig. 7, these two need to be registered. Three reference points A, B and C are created on the substrate by laser flash. B is origin of MCS and AB is on the x axis of MCS. These reference points have

corresponding points A' , B' , and C' on the design model, B' is origin point of DCS and $A'B'$ is on the x axis of DCS. The reference points are salient points and easily identified in SCS and the scanned model is transferred to MCS through the points A, B, and C in 4.2. These two models can be compared.

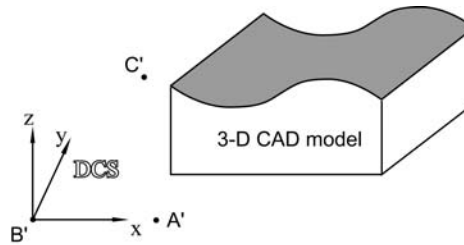


Figure 6. The 3-D CAD model created in Design Coordinate System (DCS)

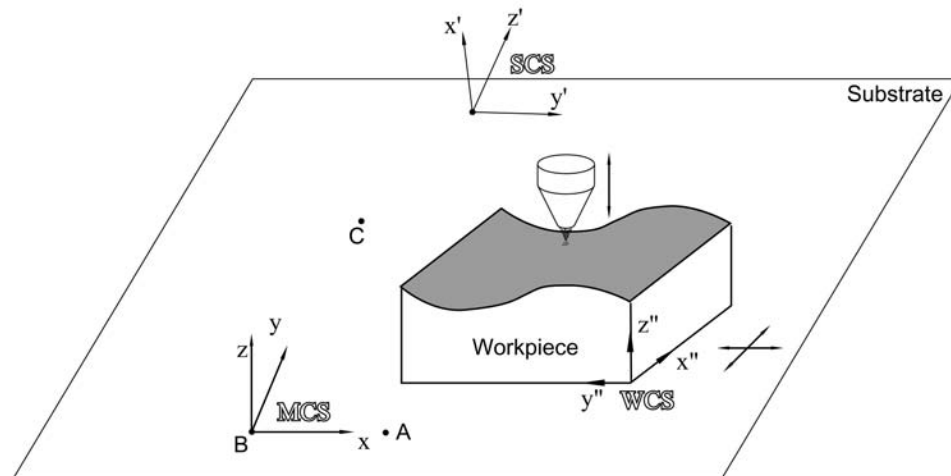


Figure 7. Workpiece is deposited in Machine Coordinate System (MCS) and scanned in Scanner Coordinate System (SCS)

4.2. Construct a coordinate system via three points

Locating a part's DCS and SCS is called localization, which refers to the determination of position and orientation of the DCS of a part with respect to the SCS. In this project, it is equal to register a part's SCS and MCS. Mathematically, it is to find a transformation matrix between the two coordinate frames [2].

The registration is a transformation between two coordinate systems, for example: transferring SCS to MCS, which is to find the matrix that transfer coordinates from $o'x'y'z'$ to $oxyz$ (Fig. 8). Suppose in SCS, the coordinate of origin O is (p'_1, p'_2, p'_3) , u_1, u_2, u_3 denote x, y, z axis and v_1, v_2, v_3 denote x', y', z' axis, then in SCS:

$$\begin{cases} u_1 = \gamma_{11}v_1 + \gamma_{12}v_2 + \gamma_{13}v_3 \\ u_2 = \gamma_{21}v_1 + \gamma_{22}v_2 + \gamma_{23}v_3 \\ u_3 = \gamma_{31}v_1 + \gamma_{32}v_2 + \gamma_{33}v_3 \end{cases} \quad (1)$$

$$\text{If } M = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix} \quad (2)$$

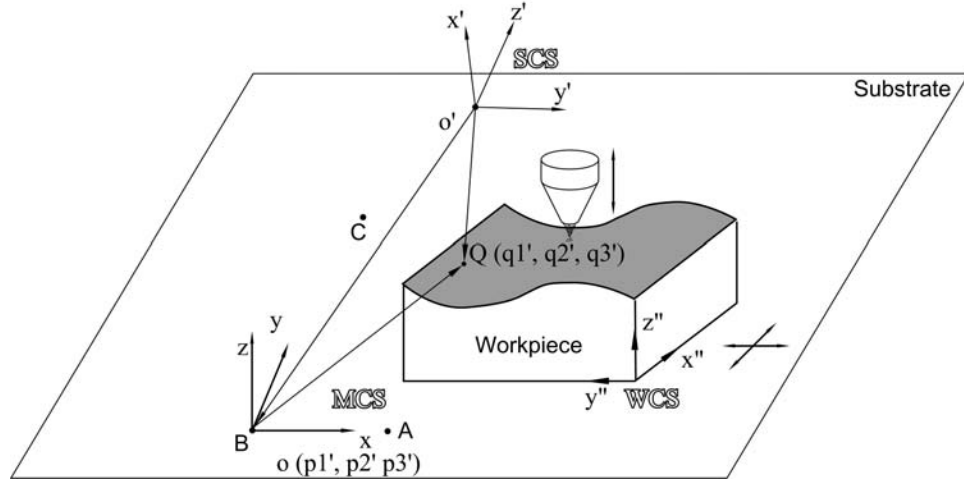


Figure 8. Mathematically, registration is to find the transformation matrix between SCS and MCS.

(1) is denoted as:

$$\begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = M \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} \quad (3)$$

An arbitrary point $Q (q'_1, q'_2, q'_3)$ in SCS denotes:

$$\overrightarrow{OQ} = [q'_1 \quad q'_2 \quad q'_3] \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} = \overrightarrow{O'O} + \overrightarrow{OQ} \quad (4)$$

$$\overrightarrow{O'O} = [p'_1 \quad p'_2 \quad p'_3] \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} \quad (5)$$

So

$$\overrightarrow{OQ} = ([q'_1 \quad q'_2 \quad q'_3] - [p'_1 \quad p'_2 \quad p'_3]) \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} \quad (6)$$

According to (3):

$$\overrightarrow{OQ} = ([q'_1 \quad q'_2 \quad q'_3] - [p'_1 \quad p'_2 \quad p'_3]) M^{-1} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} \quad (7)$$

So in SCS, an arbitrary point Q (q'_1, q'_2, q'_3) can be transferred into MCS and coordinates are:

$$([q'_1 \quad q'_2 \quad q'_3] - [p'_1 \quad p'_2 \quad p'_3]) M^{-1} \quad (8)$$

M^{-1} is the transform matrix and (p'_1, p'_2, p'_3) is coordinates of origin O in the new coordinate system MCS.

It is assumed that it is possible to have some salient points on the part or make some by marks or other methods, and these points have corresponding points on the CAD model. After scanning the surface, these points are carefully picked and the coordinates are collected on screen. Then the coordinate system can be built by these points.

Registration can have two steps: find the point to point corresponding relationship between the measurement surface and design surface, and then find the transformation

matrix between these two surfaces to construct a common coordinate system. Only three points are needed to build a coordinate system and get the transform matrix. In practical applications, the points on the measurement and 3-D model surfaces are not strictly corresponding and it needs adjustment to make them fit, for example, to make the sum of squares of distance to be the least.

In this paper, a new three-point approach is introduced. For the reason that the 3-D scanner can capture points on the surface precisely when zoomed in by the program, if there are marks or salient points on the surface, the coordinate of points can be obtained and by zoomed in, the error of on-screen point selection is about ± 0.002 inch. One of the three points is the origin, the second point and origin can determine x axis and z axis is parallel to the normal of plane of A, B, C, these two axis can determine y axis exclusively. In Fig. 9, points A, B and C are both on substrate. Point B is set to be origin in MCS and vector AB is on X axis. The coordinate system can be determined in (9). The three points are on the reference plane in order to inspect the surface relative to the reference plane. For example, the substrate is appropriate to be the reference plane for the reason that the cladding deposited from it. In this paper, a substrate is selected to be the reference plane. M^{-1} can be got from (9), and the coordinate of Q in MCS can be got from (8).

$$\begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = M \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} = \begin{Bmatrix} \frac{\overrightarrow{BA}}{|\overrightarrow{BA}|} \\ \frac{\overrightarrow{BA} \times \overrightarrow{BC}}{|\overrightarrow{BA} \times \overrightarrow{BC}|} \times \frac{\overrightarrow{BA}}{|\overrightarrow{BA}|} \\ \frac{\overrightarrow{BA} \times \overrightarrow{BC}}{|\overrightarrow{BA} \times \overrightarrow{BC}|} \end{Bmatrix} \quad (9)$$

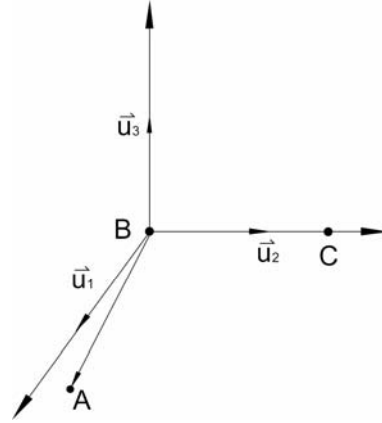


Figure 9. Three points approach to establish a coordinate system by calculating the cross product of vectors

4.3. Error Estimate

In Fig. 10, the coordinate systems xyz are created by A, B, C. The center of circle is the point in MCS, r is the deviation of these points captured in SCS. For the reason of the 3 points that are captured on screen could have errors, it leads to create deviation of SCS from MCS and coordinates of surface have some errors after transformation from SCS to MCS.

The deviation of A, B, and C on the plane have no effect on “z” coordinates of Q, but x” and “y” coordinate of Q can be affected. In Fig. 11, suppose the deviation of A, B, and C is “ r ”, the points captured could be in the circle with the radius of “ r ”. Deviation of “x” coordinate can be within $\pm r$. Deviation of “y” is depend on the coordinate of “y”, besides the errors created by the position of B, the error of point A create the angle of “ θ ”, it causes the “x” axis departure an angle “ θ ”. So the extra error created by the angle “ θ ” is scale to the “x” coordinate of Q and is equal to. When do experiments, in order to reduce the error created from captured points, the efforts are to reduce the distance of reference points A and B from point C and increase the distance of A from B, so the error of transformation is less than $2r$.

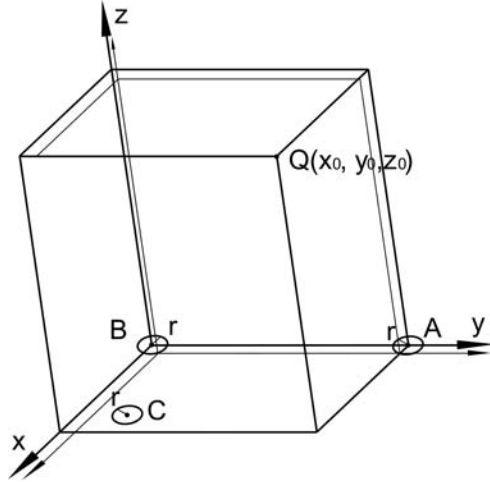


Figure 10. Errors of transformation from SCS to MCS, which is resulted from deviation of point selections

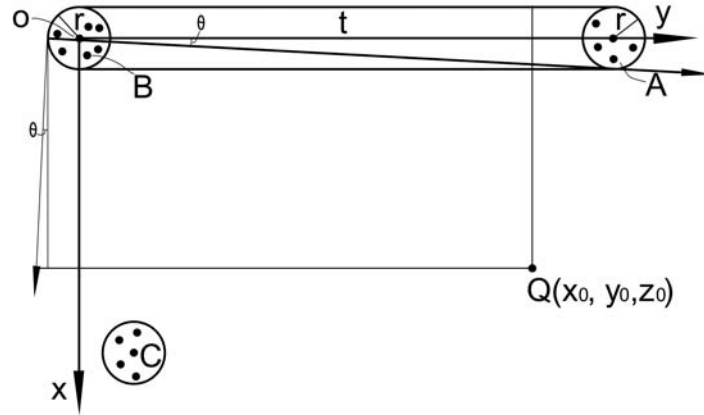


Figure 11. Error analysis of x and y coordinates for points A, B, and C on xoy plane

In Fig. 10, the coordinate systems xyz are created by points A, B, and C. The center of circle is the point in MCS and r is the deviation of these points captured in SCS. For the reason of the 3 points that are captured on screen could have errors, it leads to create deviation of SCS from MCS and coordinates of surface have some errors in SCS from MCS. In order to estimate the error r , six sample points are captured at each point of A, B in table 1. So $r=0.002$, it is higher than the accuracy of 3-D scanner, the reason is that when measure the point on the screen, it is interpolated on the triangular mesh so it is possible that it has higher resolution than that of the 3-D scanner. The nominal distance

of AB is 0.75 inch and the measurement of AB is 0.743 ± 0.004 inch, the error is at the same level as that of 3-D scanner.

Table 1. Coordinates of points A and B

Point	A		B	
	Mean	σ (STD)	Mean	σ (STD)
x	1.357 ± 0.002	1.4×10^{-3}	1.359 ± 0.001	1.5×10^{-3}
y	-1.944 ± 0.001	1.2×10^{-3}	-2.687 ± 0.001	9×10^{-4}
z	0.164 ± 0.001	1.6×10^{-5}	0.162 ± 0.001	1.5×10^{-5}

If there is no error from the point selections, the accuracy of the coordinates after transformation should keep the same as the accuracy of 3-D scanner, which is 0.005 inch. The errors of the point selections will cause the coordinates changed within ± 0.004 . The overall errors together with that of 3-D scanner, which is ± 0.0025 inch, are the sums of the two: ± 0.0065 or 0.013 inch.

V. COMPARISON BETWEEN THE MEASUREMENT SURFACE AND THE 3-D CAD MODEL

5.1. Surface description

Stereo Lithography or Standard Triangulation Language (STL) is widely used in rapid prototyping, STL model is a surface model based on triangular meshes. It makes the geometry description homogenous and no matter how complex the shape is [4]. The drawbacks of STL data format are the limited accuracy, the high data storage space needed and only the surface model left without metadata. Despite the drawbacks, the importance of STL in CAD/CAM is still increasing.

The STL data format saves the 3-D model with triangular meshes for describing 3-D surfaces. Each mesh contains a triangular data, which has its own 3 vertices coordinates and the normal vector of the triangle. In order to process the vertices data and

reduce the processing time, all the triangular data are sorted and all the description letters are removed [5].

There are at least two reasons to use the STL data format within this domain of comparing surfaces for complex shape. First, both 3-D scanner application software and the 3-D modeling tools support STL model. It allows the comparison finished in one coordinate system and data format. Second, a homogeneous STL model is fit for analysis complex (freeform) surface since it hides the complex modeling history. Freeform shapes are created from advanced operation in CAD, such as intersections, surface modeling operations, etc.

5.2. Algorithm for the comparison

By the registration process, 3-D model and measurement model are registered and the height of the top surface is along Z axis.

In order to compare deposition surface with 3-D CAD model surface, the algorithm firstly turns the 3-D surface to 2D profiles by using a series of parallel planes slicing the model, and the line segments both on the plane and the surfaces are identified, then use another group of parallel lines to slice the line segments, intersections will be calculated (Fig. 12). The distance of the intersections on two surfaces determines the relationship of these two surfaces at this point (x, y). The slicing planes are parallel to ZOY and ZOX.

The line segments both on planes and surfaces are calculated through triangles on the surfaces (Fig. 13). The algorithm scans the data and finds the triangles that intersect the plane and then calculates the intersection. In Fig. 13, the triangle on the surface has the minimum $x_{\min}=x_1$ and maximum $x_{\max}=x_3$, if x coordinate of plane ($x=x_0$) is between

the x_{\min} and x_{\max} , the plane intersect the triangle and the two intersection points are calculated as below (10):

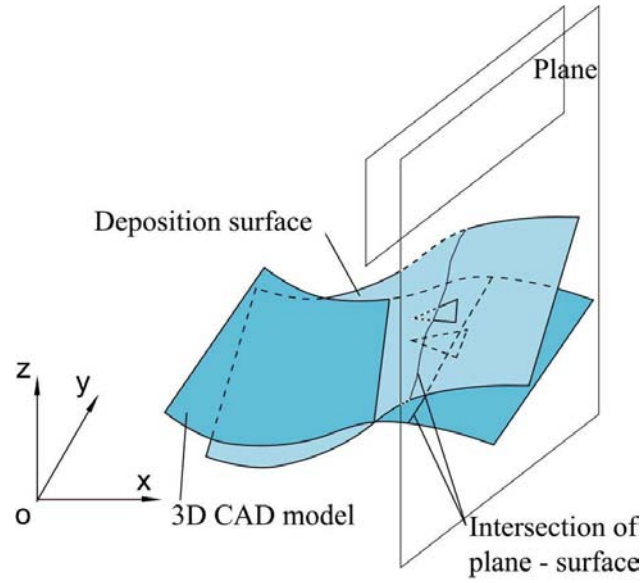


Figure 12. Comparison of two surfaces by using a group of parallel planes to slice

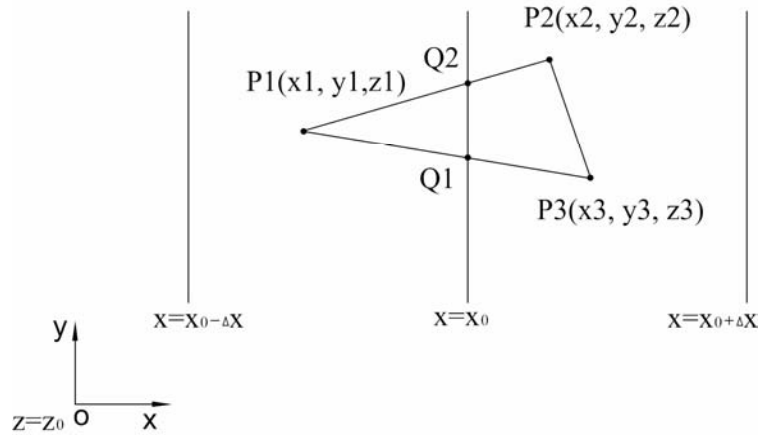


Figure 13. Intersections of plane and triangle calculated by interpolation

$$\begin{cases} Q_1 = P_1 + \frac{(P_2 - P_1)(X_0 - X_1)}{(X_2 - X_1)} \\ Q_2 = P_1 + \frac{(P_3 - P_1)(X_0 - X_1)}{(X_3 - X_1)} \end{cases} \quad (10)$$

One triangle intersects the plane $x = x_0$ at a line segment, and all the line segments compose the profile that the plane intersects the surface. A group of parallel planes, which are vertical to the previous ones, are created to slice the profiles in Fig. 14. S and T are the intersection of line segments with parallel lines, which indicate the relative height z and distance of these two surfaces at this point: $x = x_0$, $y = y_0$. S can be got:

$$S = Q_1 + \frac{(Q_2 - Q_1)(y_0 - y_1)}{(y_2 - y_1)}, \text{ and it is the same as T.}$$

In order to get higher resolution of the result, more planes are needed to slice the model and get more points on the surfaces. Calculation procedure for registration and comparison is as below in Fig. 15.

The algorithm proposed in this paper has been implemented on a PC and mainly written in Matlab.

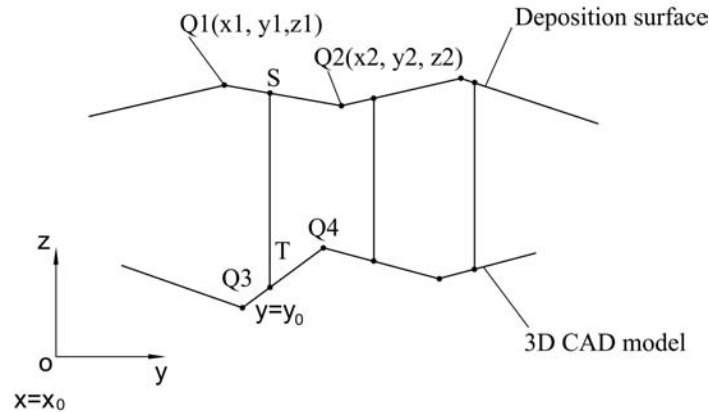


Figure 14. Intersections of planes and line segments calculated by linear interpolation

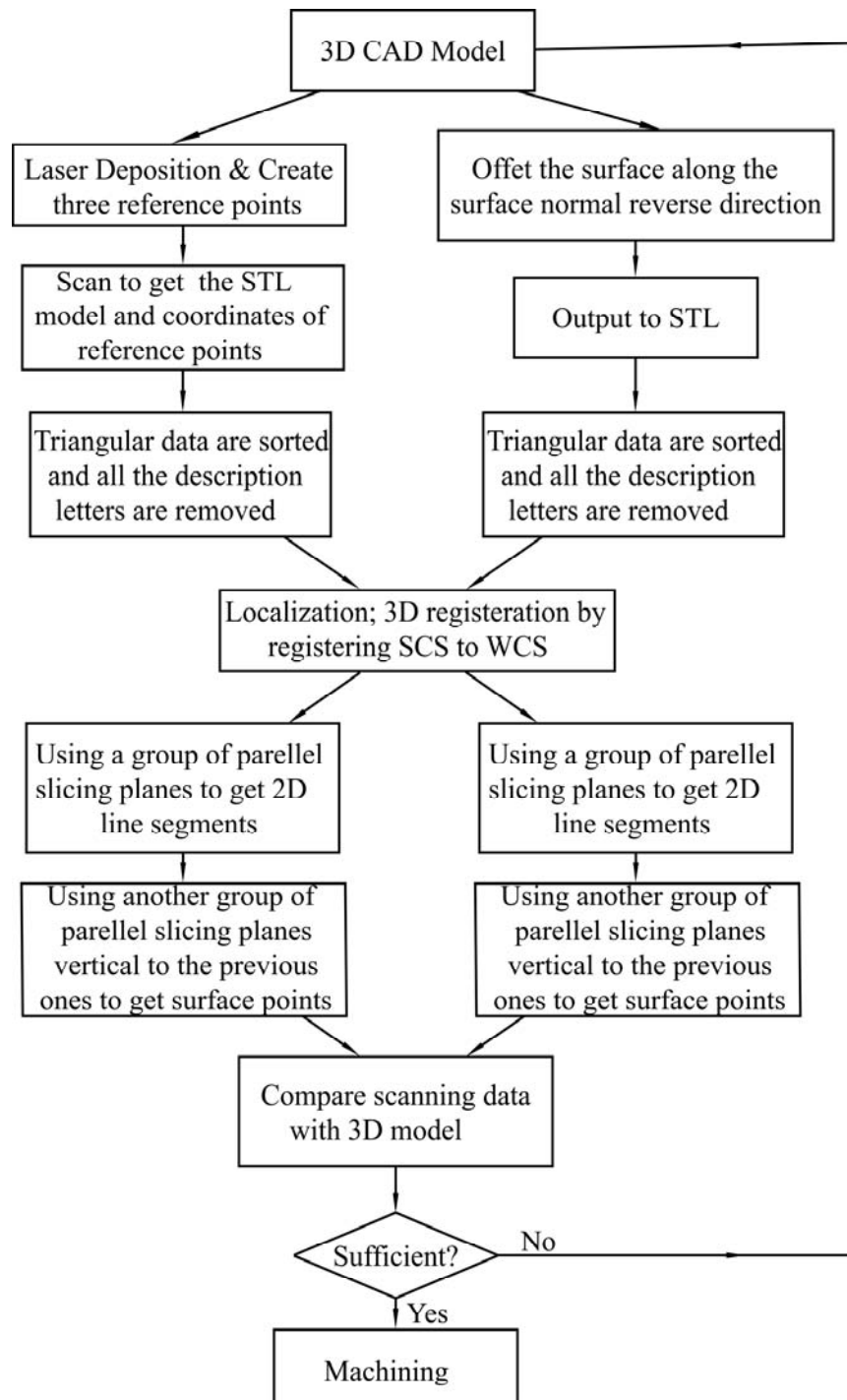


Figure 15. The procedure for registration and comparison

VI. IMPLEMENTATION

6.1. Example 1

To demonstrate the validity of the process and algorithm, a test sample is made. The 3-D scanner is installed on the CNC. After the deposition process, the part is rotated and faced to the scanner (Fig. 16). If more deposition is needed, the part will be returned to the origin deposition position without losing accuracy caused by remounting.

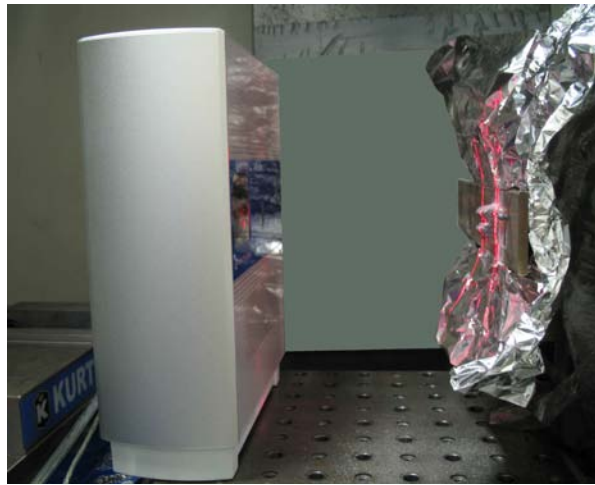


Figure 16. The scanner is set on the CNC for the on-line inspection

In Fig. 17, the 3-D CAD model of a part was designed in Solidworks. Substrate is on the XOY plane and Z axis is in the height direction. The deposition part is shown in Fig. 17. A, B, C are three reference points. The marks of A and B are made by laser flash on the substrate and C is an arbitrary point away from A and B on the substrate. The corresponding point of point B in the 3-D model is set to be origin, and the corresponding point of point A in MCS is on the x axis. After deposition, rotate the part to point to the 3-D scanner and the top surface is scanned. Registration is carried out by aligning MCS with SCS through registering the origin and the orientation of coordinate

system. On the scanner program window, the coordinates of A, B, C are captured visually by the scanner.

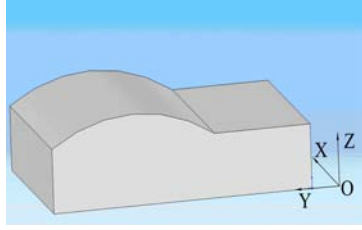


Figure 17. The 3-D CAD model created in SolidWorks

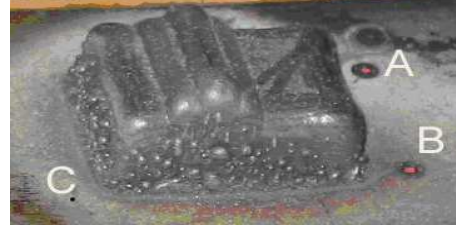


Figure 18. The deposition part with reference points A, B, and C

In SCS, coordinates of A, B, and C are (inch):

Point	x	σ	y	σ	z	σ
A	0.0130	1.3×10^{-3}	-1.9054	1.3×10^{-3}	0.1918	1.6×10^{-5}
B	1.3591	1.5×10^{-3}	-1.9441	9×10^{-4}	0.1635	1.5×10^{-5}
C	1.3599	1.3×10^{-3}	-2.6864	1.1×10^{-3}	0.1623	1.5×10^{-5}

According to (9):

$$\begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} \frac{\overrightarrow{BA}}{|\overrightarrow{BA}|} \\ \frac{\overrightarrow{BA} \times \overrightarrow{BC}}{|\overrightarrow{BA} \times \overrightarrow{BC}|} \times \frac{\overrightarrow{BA}}{|\overrightarrow{BA}|} \\ \frac{\overrightarrow{BA} \times \overrightarrow{BC}}{|\overrightarrow{BA} \times \overrightarrow{BC}|} \end{Bmatrix} = \begin{Bmatrix} -0.9994v_1 - 0.0287v_2 + 0.0209v_3 \\ 0.0287v_1 - 0.9996v_2 - 0.0017v_3 \\ 0.0210v_1 - 0.0016v_2 + 0.9998v_3 \end{Bmatrix}$$

$$\text{So } M^{-1} = \begin{bmatrix} -0.9994 & -0.0287 & 0.0209 \\ 0.0287 & -0.9996 & -0.0017 \\ 0.0210 & -0.0016 & 0.9998 \end{bmatrix}$$

An arbitrary point Q (q'_1, q'_2, q'_3) in SCS can be transferred into MCS according to (8):

The distance between the slicing planes or the resolution is 0.005 inch. In Fig. 19, those two models are registered. After comparison of two surfaces, the sufficient area and insufficient area are identified in Fig. 20 and 21, respectively. The average height of the cladding above the 3-D model is 0.108 inch in the middle area. But on the edge, at most about 0.07 inch area is insufficient and the reason is that the cladding wall can not keep straight and vertical to the substrate across the wall. When design the part, an offset of 0.10 inch was added to the target 3-D model along the wall surface normal direction to overbuild it in order to counteract it and to ensure it has sufficient volume to machine a part afterwards. The overbuilt on the wall depends on the height of the cladding H and the tilt angle θ of the wall from the normal direction of the substrate, the overbuilt thickness $S = H \tan \theta$. θ is estimated to be around $10^\circ \sim 15^\circ$ (Fig. 22). However, if missing information is not easily estimated like this example, a complete scan model is needed by scanning and registering several scan of facets.

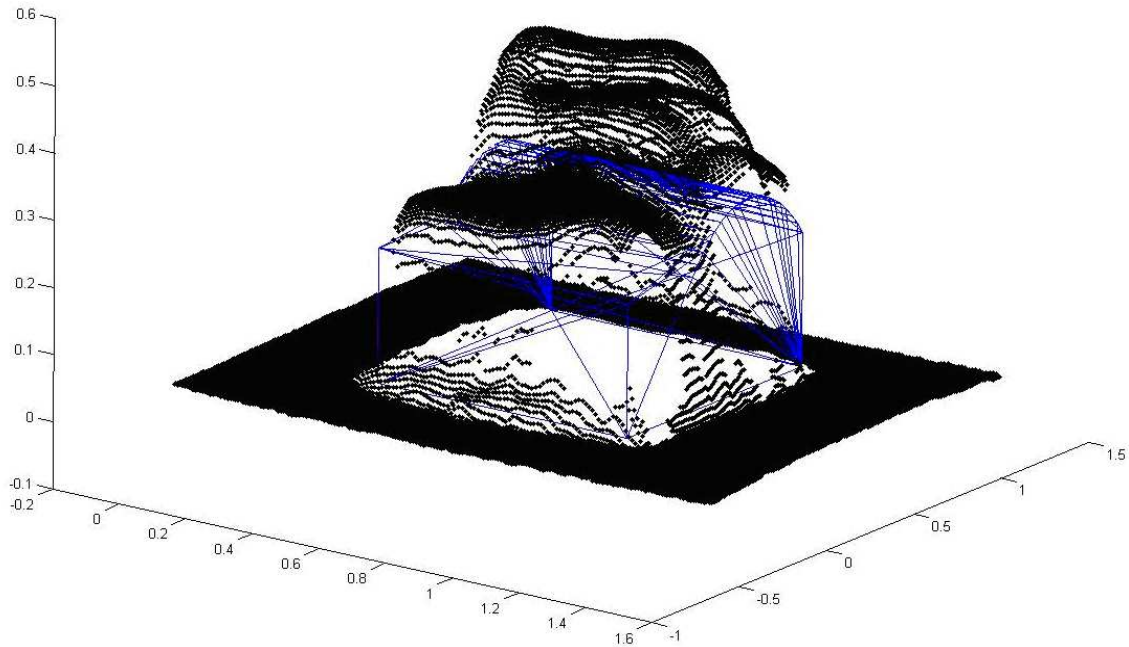


Figure 19. The scanned model and 3-D CAD model are registered

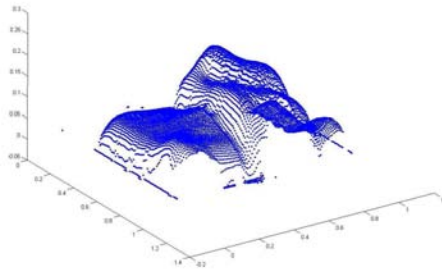


Figure 20. The extra volume of cladding after the measurement data subtracts 3-D model

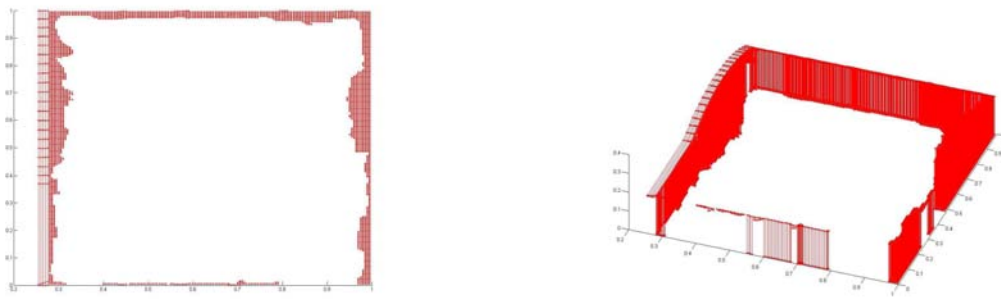


Figure 21. The insufficient volume (left: top view, right: 3-D view)

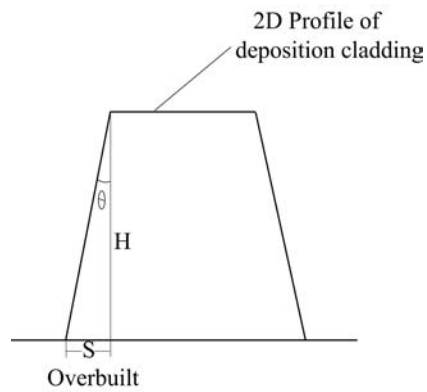


Figure 22. Overbuild volume of vertical wall for counteracting the tilt wall

6.2. Example 2

Another example is made in Fig. 23 for design model and in Fig. 24 for deposition. The part is scanned and all the surface information is captured by one scan. In

Fig. 25, the two are plotted in one coordinate system, they are separated and in different orientation. In Fig. 26, the two are registered and two models are compared.

After comparison of two surfaces, the sufficient area and insufficient area can be identified respectively. In Fig. 27, one slice shows the deposition cladding is sufficient at that location. Fig. 28 shows multiple slices that the deposition surface subtracts the design model surface. There are sufficient volumes on these slices. If all the slices show the same result, it can conclude that the deposition is sufficient for fabricating a part. Otherwise, a repair process or re-deposition is needed. In Fig. 28, it shows the cladding is sufficient.

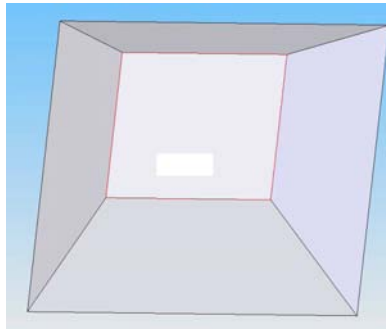


Figure 23. The 3-D CAD model created in SolidWorks



Figure 24. The Deposition part with reference points A, B, and C

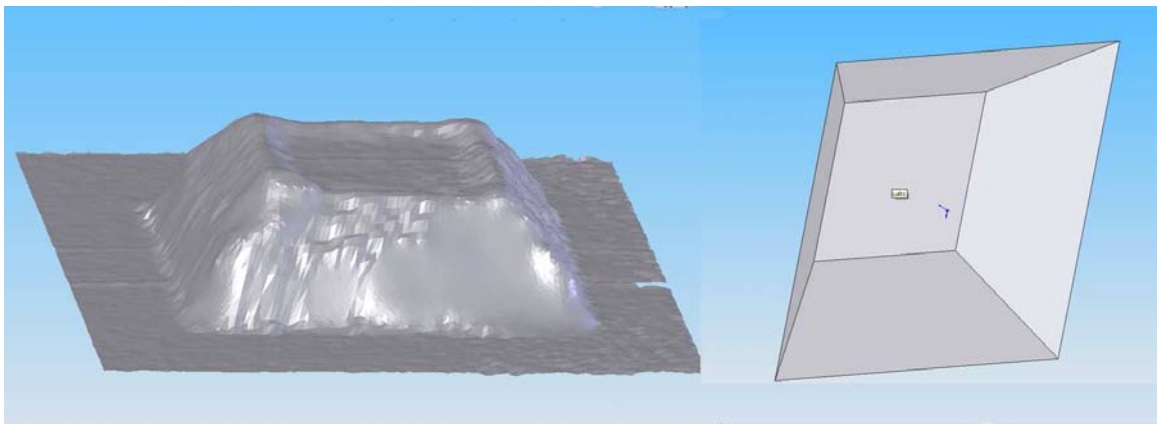


Figure 25. Scanned model and design model, which are separated and in different orientation before registration, can not be directly compared

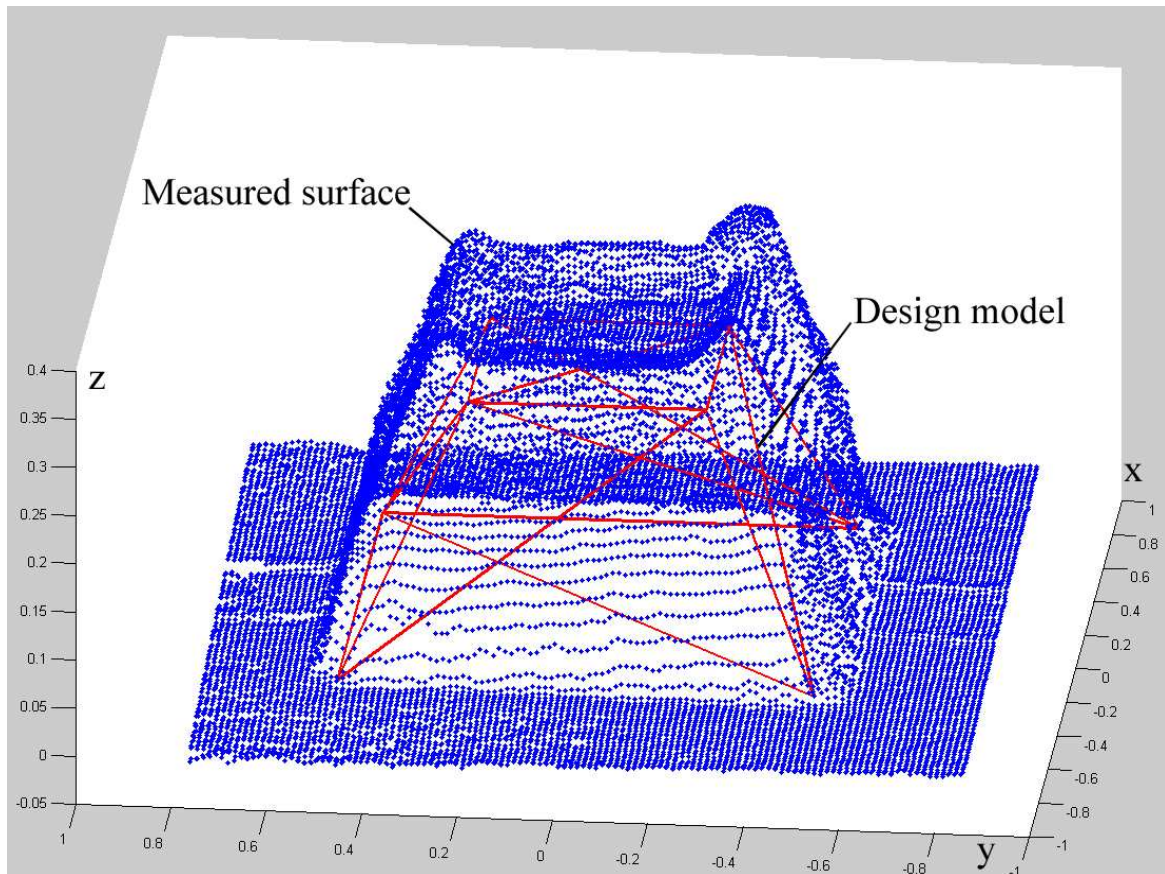


Figure 26. The scanned model and design model are registered and comparable

6.3. Example 3

In Fig. 29, it shows a part deposited by Titanium powder. After one scan from the top, the model is successfully captured. Fig. 30 plots the scanned measurement models in SolidWorks. The comparison can be performed and similar to example 1.

6.4. Example 4

However, if one scan can not get the complete surface information and the missing volume can not be estimated easily by overbuilt volume, more scan is needed to construct a complete model. In Fig. 31, it shows a part that has missing information and the walls are designed with a tilt angle about 60 degree and it is important to get all the information. Therefore a complete model is built with four scan and then to register these

images via the reference points marked on the surface in the software of operating the scanner in Fig. 32. The comparison can be performed similarly as examples 1 and 2.

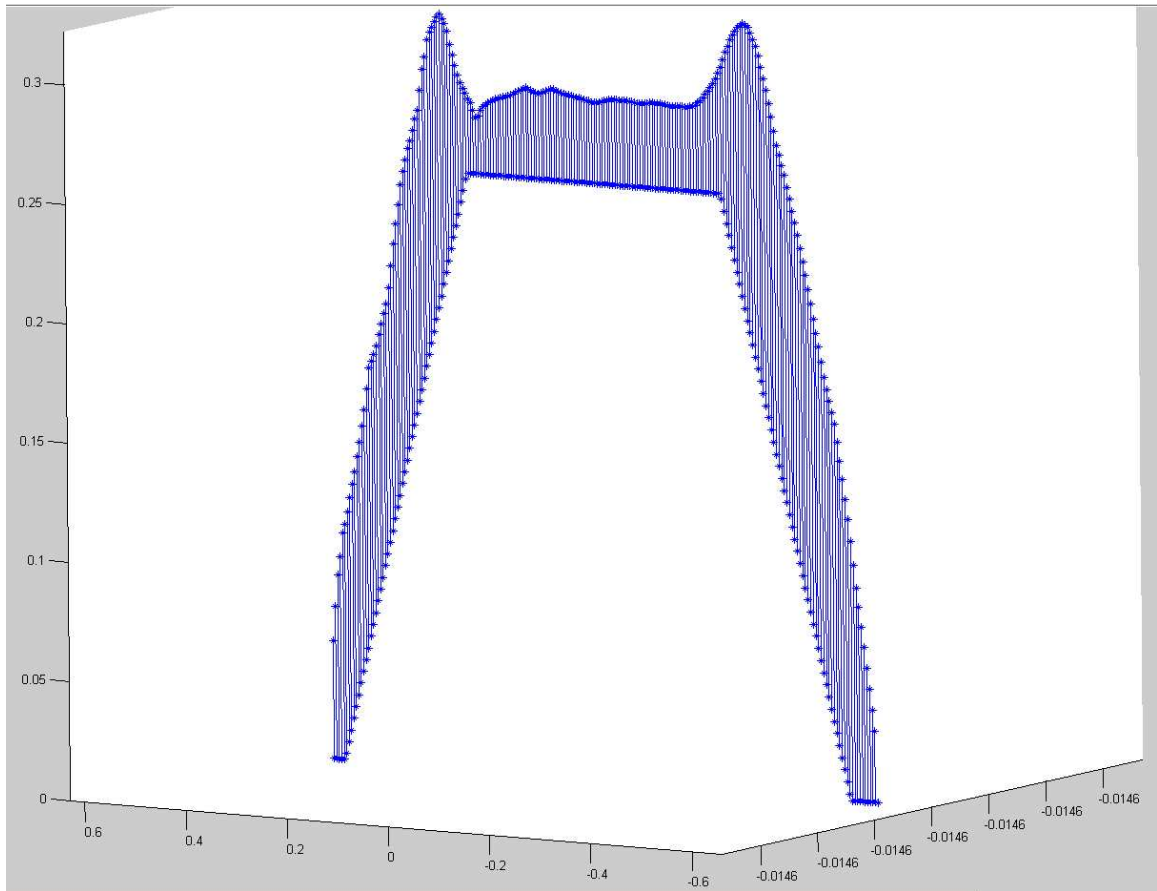


Figure 27. One slice shows the extra volume of cladding after the measurement data subtracts 3-D model

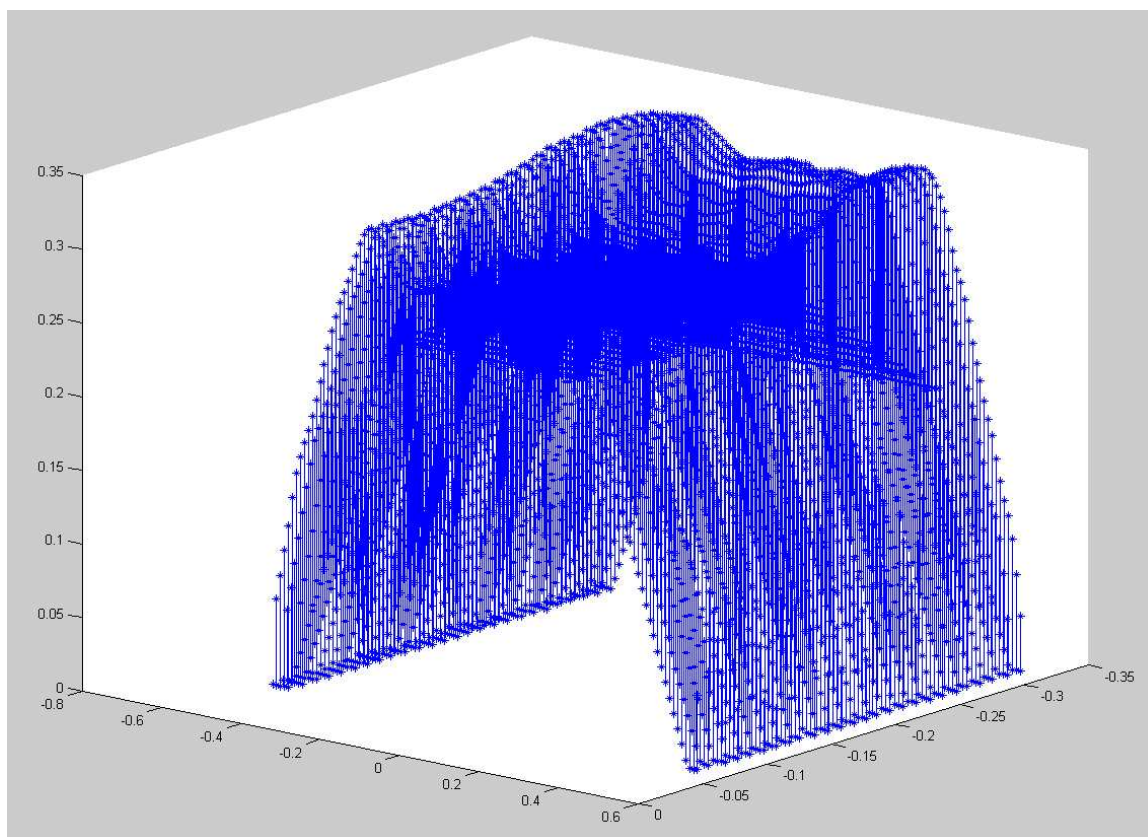


Figure 28. Multiple slices show the extra volume of cladding after the measurement data subtracts 3-D model (to illustrate, only half of the slices are plotted and the distance between slices is 0.01 inch)



Figure 29. The part is deposited by Titanium powder

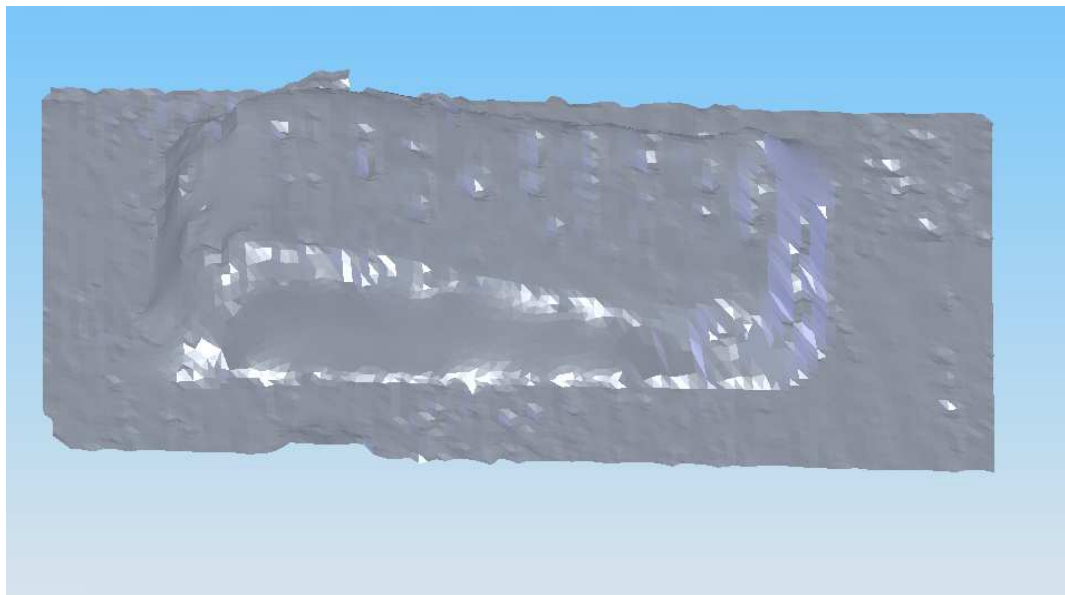


Figure 30. The scanned measurement model is plotted in SolidWorks

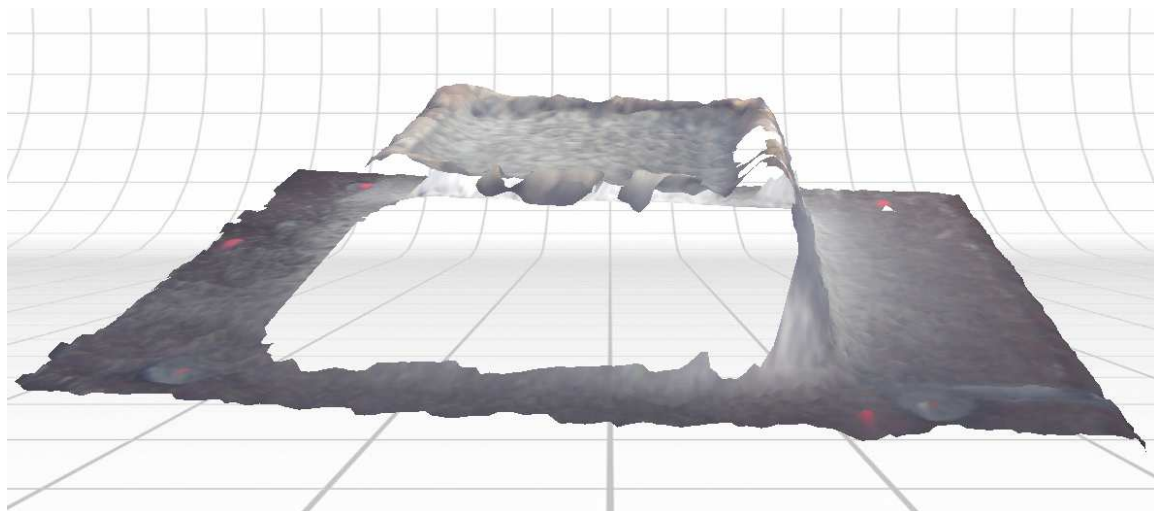


Figure 31. There is missing area on the surface after scanning a part with steep curvature feature

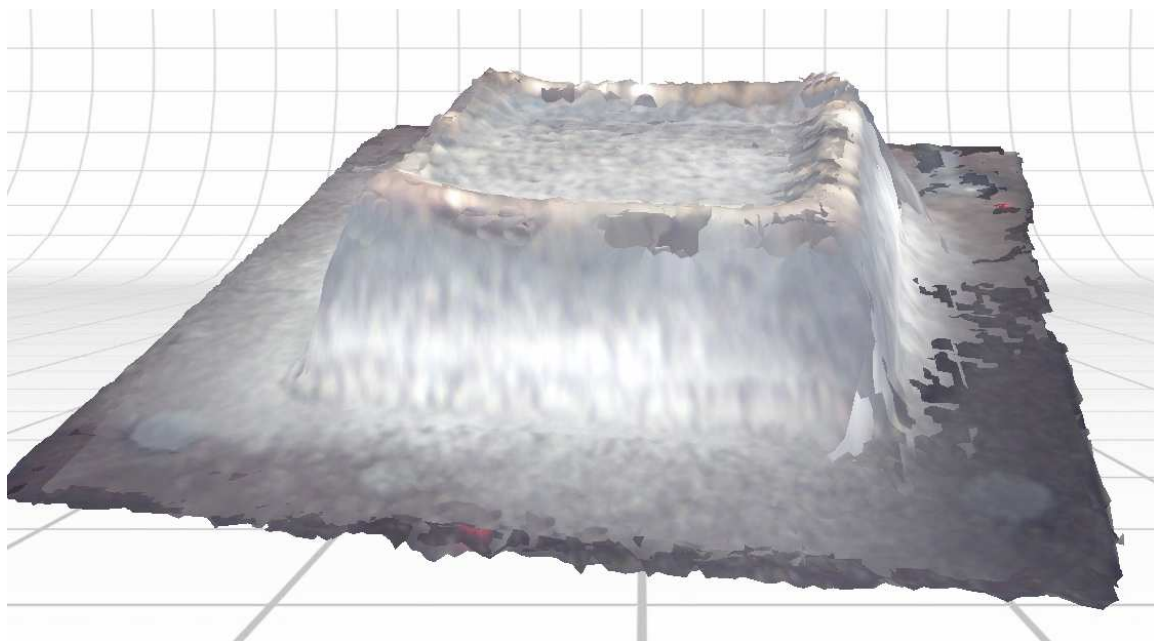


Figure 32. By registering four scan images captured in different view angles, the complete model is built

VII. SUMMARY AND CONCLUSION

This paper describes how to compare the laser deposition surface and its target - 3-D model using a 3-D scanner to do a no-contact top surface measurement.

Based on the approach of registration and comparison algorithm, measurement data is aligned with 3-D model, which needs three reference points, and the comparison between top surfaces of deposition cladding and 3-D model is conducted. It determines if the deposition cladding is sufficient for fabricating a part according to the comparison before machine the part.

The overall accuracy of this method is 0.013 inch and it fulfills the requirement of laser deposition.

The advantage of this method is that it is fast and convenient to inspect the deposition cladding. The disadvantage is that it can not perform real-time inspection for environmental condition. Also if the surface has steep curvature, a complete scanning model will be needed to perform the comparison.

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Paper II

COMPARISON OF THERMAL PROPERTIES OF LASER DEPOSITION AND TRADITIONAL WELDING PROCESS VIA THERMAL DIFFUSIVITY MEASUREMENT

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Abstract

Laser deposition is an effective process for mold and die repair. In order to improve the part repair quality, the process impact on thermal diffusivity and thermal conductivity needs to be understood for laser deposited, welded and virgin H13. In this paper, H13 tool steel samples were made by laser deposition, welding and virgin H13 and then cut into pieces. Experiments were conducted to investigate the thermal diffusivity and conductivity. A laser flash method is used to test these samples. The future work and opportunities are also summarized.

Keywords

Laser Flash, laser deposition, tool steel H13, Welding

1. Introduction

Currently part repair technology is gaining more interest from military and industries due to the benefit of cost reducing as well as time and energy saving. Traditionally, part repair is done in the repair department using welding process. The

limitations of the traditional welding process are becoming more and more noticeable when accuracy and reliability are required [1]. In addition, the life of the mold and die parts after being repaired by welding process is much shorter than that of the virgin metal according to industrial experience. In LAMP (Laser Aid Manufacturing Process) lab, the laser deposition process is developed to repair the parts (Fig. 1), for example the worn die shown.



Figure 1. The die after repaired by laser deposition and machined by CNC

Thermal conductivity and thermal diffusivity play an important role in the life of molds and dies. Higher thermal diffusivity means that thermal equilibrium will be reached faster when the temperature changes. A good thermal diffuser will react more quickly to environmental temperature changes. Higher thermal conductivity equates to the transfer of more thermal energy per unit of time under steady state conditions [2]. In this paper, different samples of tool steel made by virgin, welding and laser deposition were prepared and the thermal properties of these samples were investigated by the laser flash method.

2. Theory of experiment

Laser flash method was first introduced by Parker, Jenkins etc in 1960 [1]. The front surface of a thin sample is heated instantaneously and heat conducts through the sample. The back surface temperature T vs. time t has this relationship:

$$T(L,t) = \frac{Q}{\rho CL} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left(-\frac{n^2 \pi^2}{L^2} \alpha t\right) \right] \quad (1) [3]$$

where Q is the radiant energy incident on the front surface at $t=0$, ρ is density, C is specific heat and α is thermal diffusivity, L is the thickness of the sample.

Two dimensionless parameters, V and ω can be defined:

$$V(L, t) = T(L, t) / T_M \quad (2) [3]$$

$$\omega = \pi^2 \alpha t / L^2 \quad (3) [3]$$

T_M represents the maximum temperature of back surface. The combination of 1, 2 and 3 yields:

$$V = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-n^2 \omega) \quad (4) [3]$$

Equation (4) is plotted in Fig. 2:

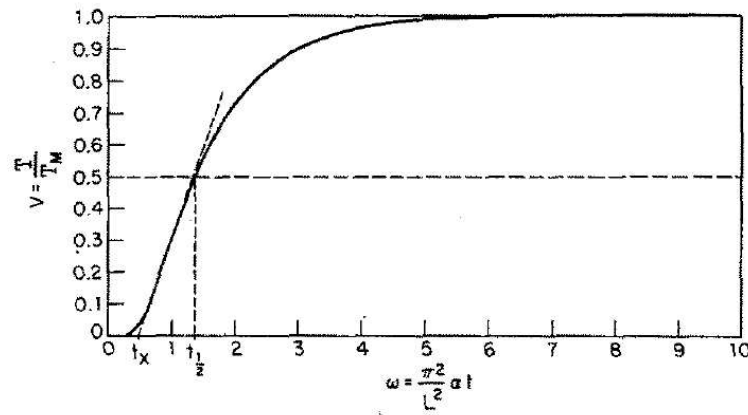


Figure 2. Dimensionless plot of back surface temperature history [3]

One way of determining α has been deduced from (4) and Fig.2. When V is equal to 0.5, ω is equal to 1.38, so

$$\alpha = \frac{0.1388}{t_{1/2}} L^2 \quad (5) [3]$$

Where $t_{1/2}$ is the time required for the back surface to reach half of the maximum temperature rise.

Thermal conductivity λ is calculated using the value of thermal diffusivity and specific heat.

$$\lambda = \alpha \cdot C_p \cdot \rho \quad (6) [3]$$

(α : Thermal diffusivity, ρ : Density, C_p : Specific heat, is determined by this laser pulse and almost equal to the energy of the laser)

3. Experiment setup

The purpose of the experiment is to test $t_{1/2}$ - the time required for the back surface to rise to half of the maximum temperature it can reach according to equation (5). The front face of a small disk-shaped sample was subjected to a very short burst of radiant energy. The source of the radiant energy is a laser irradiation. The resulting temperature rise of the rear surface of the sample is measured and recorded by the real time system.

Fig. 3 shows the experiment design. The experiment system contains laser, real-time system and temperature sensor. The laser pulse and data record are both controlled by real-time system. The laser was a 50 watt Diode laser with very short pulse at about 5ms. The temperature sensor is RTD (Resistance Temperature Detector) (Fig. 4), in order to achieve good heat conduction from sample to the sensor, thermal grease was applied in between the sensor and samples. A thermal couple was used before as the temperature sensor. However, RTD is more accurate and has been developed to be so small that it fit for very tiny sample. The infrared (IR) sensor is also applied in many systems for recording the temperature rise curve [4]. It can measure thermal properties at very high temperature. We chose RTD over an IR sensor for the reason that it is simpler and effective.

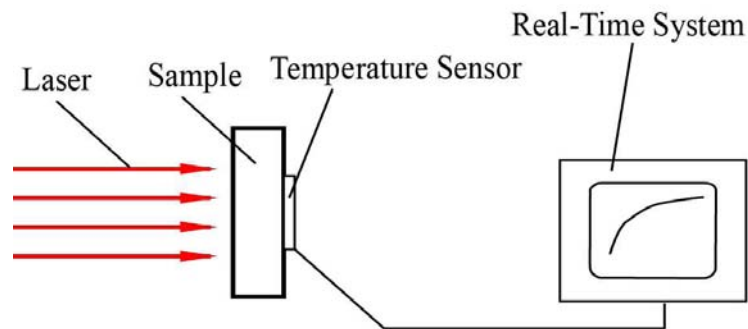


Figure 3. Laser flash method experiment design

The hardware and software of the Real-time System come from National Instrument and the program was based on the Lab-view 8. The real-time system can achieve two functions: control laser to create laser pulse in desired duration, measure and record the back face temperature of samples through the RTD sensor.

4. Sample preparation

Laser deposition cladding, welding cladding and virgin tool steel samples, which are all tool steel H13, were cut into small pieces with the size of 5mmX5mmX2mm. The thickness of the samples was important for the test, the thinner the more precise for the experiment.

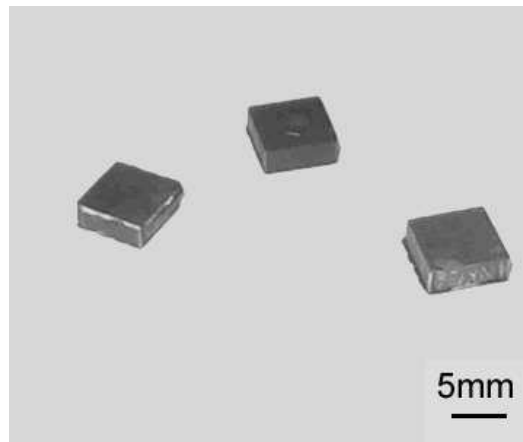


Figure 4. Specimens

5. Experiment

The sample was placed on the RTD sensor and the laser nozzle was aligned. The real-time system controls the laser to flash on the front side of the sample to heat the sample and record the rise curve of the back side temperature of the sample simultaneously. A typical temperature rise curve is shown in Fig. 5. The value of $t_{1/2}$ was measured as shown in Fig. 5 and the thermal diffusivity and thermal conductivity was calculated according to equation 5 and 6. For virgin, welding and laser deposition tool

steel samples, we assume all samples had the same density and specific heat: $C_p=0.45$ J/g-c, $\rho=7.8 \times 10^3$ kg/m³.

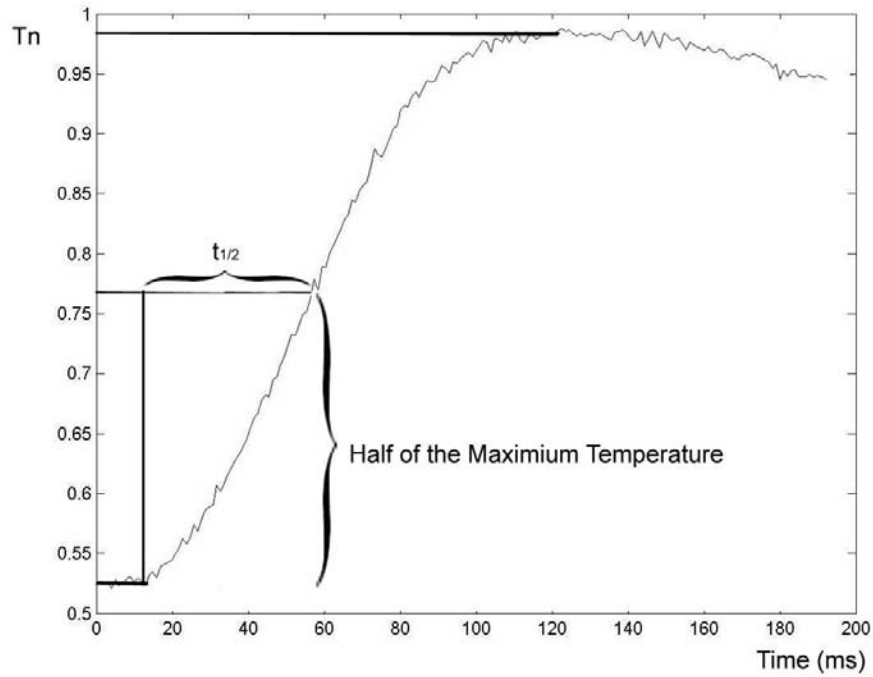


Figure 5. Typical back-face temperature vs. time rise curve of tool steel samples

6. Result

Six specimens were prepared for the experiment, two for virgin metal, two for laser deposition and two for welding. Each sample had three replicates. The results are shown in table 1:

The uncertainties of thermal diffusivity and conductivity come from the error of thickness L and $t_{1/2}$:

$$\Delta\alpha = \left| \frac{2 \times 0.1388}{t_{1/2}} L \right| \times |\Delta L| + \left| -\frac{0.1388}{t_{1/2}^2} L^2 \right| \times |\Delta t_{1/2}| \quad (7)$$

$$\Delta\lambda = Cp\rho\Delta\alpha \quad (8)$$

The virgin samples can be regarded as the reference samples, and the thermal conductivity of virgin samples is in the range it should be - around 20 W/mK. Both laser deposition and welding specimens have lower average thermal conductivity than virgin

H13, welding drops about 43% and laser deposition drops about 1/3, but laser deposition has higher average thermal conductivity than welding by 22%.

Table 1- Thermal Conductivity Experimental Results

	No.	Size (mm)	Thickness (mm) ± 0.001	$t_{1/2}(s)$ ± 0.005	Average Thermal Diffusivity ($\times 10^{-6} m^2/s$)		Average Thermal conductivity (W/mK)	
Virgin part	#1	5.0X5.0	2.011	0.102	5.5 ± 0.3	5.7 ± 0.6	19.7 ± 1.1	20.3 ± 2.2
	#2	5.0X5.0	2.028	0.098	5.8 ± 0.3		20.9 ± 1.1	
Welding	#3	5.0X5.0	2.008	0.173	3.2 ± 0.1	3.0 ± 0.2	11.6 ± 0.4	11.5 ± 0.9
	#4	5.0X5.0	2.055	0.185	2.8 ± 0.1		11.4 ± 0.5	
Laser deposition	#5	5.0X5.0	2.039	0.167	3.7 ± 0.1	3.77 ± 0.2	13.1 ± 0.4	13.5 ± 0.8
	#6	5.0X5.0	2.012	0.145	3.9 ± 0.1		13.9 ± 0.4	

7. Analysis

There are many reasons why the different sample types have different thermal properties. Laser deposition has small heat affected zone than conventional welding, so that laser deposition has more homogenous microstructure, it is one of the reasons why welding samples have lower thermal diffusivity and conductivity than laser deposition samples.

8. Conclusion

In this paper, the laser flash method to measure thermal diffusivity was introduced. The experiment system based on the laser flash method was designed and conducted. The results show that repaired H13 tool steel parts have lower thermal diffusivity and conductivity than virgin metal and the parts repaired by laser deposition have higher thermal diffusivity and conductivity than those repaired by traditional

welding. It means that laser deposition process will be better for part repair considering the thermal diffusivity and thermal conductivity than traditional welding process.

The next step is to study the microstructure and compare the difference between laser deposition, welding and virgin tool steel H13. Also the samples are tested at the room temperature. Thermal properties of the samples at higher temperature should be investigated and a furnace will be added on this system and to keep the samples at proper constant temperature.

Acknowledgement

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VITA

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